Available online at www.sciencedirect.com

SCIENCE DIRECT

Renewable and Sustainable Energy Reviews
8 (2004) 545–563

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Geothermal energy in Turkey: the sustainable future

Kamil Kaygusuz [a,*], Abdullah Kaygusuz [b]

[a] *Department of Chemistry, Karadeniz Technical University, 61080 Trabzon, Turkey*
[b] *Department of Geological Engineering, Karadeniz Technical University, Trabzon, Turkey*

Received 6 January 2004; accepted 6 January 2004

Abstract

Turkey is an energy importing nation with more than half of our energy requirements met by imported fuels. Air pollution is becoming a significant environmental concern in the country. In this regard, geothermal energy and other renewable energy sources are becoming attractive solution for clean and sustainable energy future for Turkey. Turkey is the seventh richest country in the world in geothermal energy potential. The main uses of geothermal energy are space heating and domestic hot water supply, greenhouse heating, industrial processes, heat pumps and electricity generation. The district heating system applications started with large-scale, city-based geothermal district heating systems in Turkey, whereas the geothermal district heating centre and distribution networks have been designed according to the geothermal district heating system (GDHS) parameters. This constitutes an important advantage of GDHS investments in the country in terms of the technical and economical aspects. In Turkey, approximately 61,000 residences are currently heated by geothermal fluids. A total of 665 MW_t is utilized for space heating of residential, public and private property, and 565,000 m^2 of greenhouses. The proven geothermal heat capacity, according to data from existing geothermal wells and natural discharges, is 3132 MWt. Present applications have shown that geothermal energy is clean and much cheaper compared to the other fossil and renewable energy sources for Turkey.

* Corresponding author. Fax: +90-462-325-3195.
E-mail address: kaygukm@tnn.net (K. Kaygusuz).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.01.001

Contents

1. Introduction

At the turn of the millennium, two billion people, a third of the world's population, have no access to modern energy services. World population is expected to double by the end of the 21st century. A key issue to improve the standard of living of the poor is to make clean energy available to them at prices they can afford. Energy affects all aspects of modern life. There is a strong positive correlation between energy use per capita in a country and issues that we value highly such as productivity per capita in the country and life expectancy [1].

The World Energy Council has presented several scenarios for meeting the future energy requirements with varying emphasis on economic growth, technological progress, environmental protection and international equity. During the period 1990–2050, the primary energy consumption is expected to increase by 50% according to the most environmentally conscious scenario and by 275% according to the highest growth rate scenario. In the environmental scenario, carbon emissions are expected to decrease slightly from 1990 levels, whereas the high growth-rate scenario leads to a doubling of carbon emissions. The scarcity of energy resources forecasted in the 1970s has not occurred so far. Economic development in the new century will not be constrained by geological resources. Environmental concerns, financing, and technological constrains appear more likely sources of future limits [2].

Geothermal energy use avoids the problems of acid rain, and it greatly reduces greenhouse gas emissions and other forms of air pollution. Geothermal reservoirs, either dry steam or hot water, are naturally occurring hydrothermal convection systems. Natural fluids are usually complex chemical mixtures, and geothermal waters exhibit a wide range of compositions and concentrations of solutes. The concentration of solutes generally increases with the temperature of the geothermal system, and higher concentrations of some elements often require remedial action for protection of the environment. Potentially hazardous elements such as Hg, B, As and Cl are produced in geothermal brines and are largely injected back into the producing reservoir. A continuing strong market for geothermal electrical gener-

ation is anticipated as a result of the increasing interest in controlling atmospheric pollution and because of the spreading concern about global warming. Geothermal development will serve the growing need for energy sources with low atmospheric emissions and proven environmental safety [3].

People have used hot springs for bathing and washing of clothes since the dawn of civilization in many parts of the world. The Etruscans, Romans, Greeks, Indians, Chinese, Mexicans, and Japanese have all left evidence that they used hot water in ancient times, where these waters were commonly thought to have healing properties. Since the 8th century AD, the Japanese have used thermal waters for body purification, which is the first step in the purification of the spirit, and many hot spring sites have temples dedicated to the Buddha of Medicine. The Romans also used thermal springs for recreational purposes. They built spas all over the Mediterranean area, and to the furthest boundaries of their empire, for example at Bath in England, thus spreading their knowledge of the beneficial effects of thermal waters. On the other hand, in the Middle Ages, Arabs and Turks developed and diffused the traditional use of thermal baths, later known as Turkish baths, whose rich and sensual atmosphere is well depicted by the French painter Ingres in his masterly The Turkish Bath (1863, Louvre). These uses were to lead the way to the modern balneological industry [3].

For example, the city of Bursa is situated to the south of the Marmara Sea at the northern slope of the highest mountain in western Turkey (Mount Uludağ, 2543 m above sea level) on a large travertine complex. Bursa was the first Ottoman capital (1326–1451), and has grown into one of the largest cities in Turkey, with a population of over 800,000. Thermal waters with temperatures up to 46 and 82 $^{\circ}$C discharge within the two districts of Çekirge and Kükürtlü at the western end of Bursa city, just above the plain. As with many other geothermal systems in western Turkey, the circulation of the Bursa thermal waters is also closely related to a major fracture zone. On the other hand, although several important normal faults separate Mount Uludağ from the plain, thermal water discharges only in its westernmost part, in the two districts of Çekirge and Kükürtlü. The Bursa thermal waters at Çekirge and Kükürtlü are now used for bathing and medicinal purposes. Due to the differences in water temperature and chemistry the two thermal water resorts have developed in different ways [4].

The present paper describes the status of geothermal energy development in Turkey. In this paper explorations regarding the importance of geothermal energy for Turkey, its research and development, present and probable applications, contribution to economy, technical level reached by (Mineral Exploration and Research Directorate (MTA) and other private companies and expectations also be given. The main uses of geothermal energy in Turkey are: space heating and domestic hot water supply, greenhouse heating, balneology, CO_2 and dry-ice production, ground-source heat pumps and electricity generation.

2. Present energy situation in Turkey

Energy issues are directly related to the development of a country and the living standards of its people. Turkey is currently in a rapid industrialization process with a young and dynamic population of over 65 million. Due to relatively high growth rate of the population, increasing consumer oriented attitudes and as a result of rising levels of affluence, the primary energy demand is rising rapidly at an average annual rate of 6.8%. Turkey is currently projected to remain a net importer of energy, with more than 60% of its needs to be imported in 2020.

Turkey's national energy policies are designed to provide the required energy on a timely, reliable, cost-effective, environmentally friendly and high-quality basis so as to serve as the driving force of development and social progress. On the other hand, meeting such a demand requires critical planning, and within this framework, the Ministry of Energy and Natural Resources (MENR) is currently aiming for the year 2020. Supply and demand projections constitute the basis of these policies and the ongoing work is continuously updated within the context of national and international developments. Moreover, the legal and institutional arrangements needed for reliable and sustainable future supplies of energy are emerging as a matter of government responsibility.

Turkey is an energy importing country; more than half of the energy requirement has been supplied by imports (Table 1). Oil has the biggest share in total primary energy consumption. The high level of dependence on imported petroleum and natural gas is the dominant factor in Turkey's pattern of energy consumption. The share of petroleum and natural gas in consumption of commercial primary energy rose from 60% and 20% in 1990 to 70 and 40% in 2000, respectively. The oil and natural gas import bill grew rapidly, surpassing total export earnings in 1990, and become a major contributing factor to the 1979 and 2001 economic difficulties. In order to reduce Turkey's dependence on imported oil, the government launched

Table 1
Primary energy production and consumption of Turkey during 1998–2001 (Mtoe)

	Energy production				Energy consumption			
	1998	1999	2000	2001	1998	1999	2000	2001
Hard coal	1.678	2.729	1.769	1.255	8.160	11.286	8.149	6.972
Lignite	12.514	12.685	12.830	12.772	12.414	12.984	12.830	13.091
Oil	3.230	3.056	2.925	2.679	32.083	32.916	34.893	30.721
Natural gas	0.684	0.662	0.631	0.284	10.635	12.902	14.071	14.967
Total fossil	18.106	19.132	18.155	16.990	63.292	70.088	69.943	65.751
Hydropower	3.632	2.982	2.656	2.072	3.632	2.982	2.656	2.072
Geothermal	0.256	0.274	0.286	0.310	0.256	0.274	0.286	0.310
Solar	0.098	0.114	0.120	0.130	0.098	0.114	0.120	0.130
Wood	5.512	5.293	5.081	5.060	5.512	5.293	5.081	5.060
Waste & Dung	1.492	1.510	1.376	1.372	1.492	1.510	1.376	1.372
Total renewable	10.878	10.650	9.519	8.945	10.878	10.650	9.519	8.945

Source: Ref. [7].

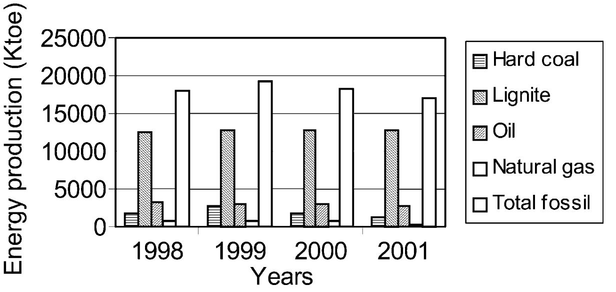

Fig. 1. Primary fossil energy production in Turkey.

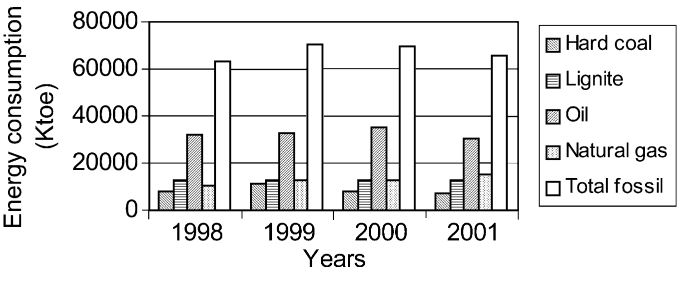

Fig. 2. Primary fossil energy consumption in Turkey.

a massive program in the late 1970s and 1980s to increase the domestic production of electricity and lignite. This program has stretched the implementation capabilities of the State energy agencies to their limit beyond.

Turkey's primary energy sources include lignite, hard coal, oil, natural gas, hydropower, geothermal, wood, animal and plant wastes, solar and wind energy. Turkey has large reserves of coal, particularly of lignite. The proven lignite reserves are 8.0 billion tons. The estimated total possible reserves are 30 billion tons. A majority of these lignite mostly situated in Afşin-Elbistan, Soma and Tunçbilek are characterized with high ash contents in the range of 14 to 42%, high moisture contents ranging from 15 to 50% and volatile matter contents of 16–38%. In 2001, primary energy production and consumption has reached 26 and 74.7 million tons of oil equivalent (Mtoe) respectively. Figs. 1 and 2 show the primary fossil energy production and consumption between 1998 and 2001 in Turkey, respectively.

As for electric power, the installed capacity of Turkey reached 23,264 MW and the annual gross per capita consumption of electricity reached 1784 kWh at the end of 1998. Total electrical energy consumption was 114 billion kWh in 1998. This annual figure is estimated to reach 200 billion kWh in 2005, 290 billion kWh in 2010, and 547 billion kWh in 2020. To meet this demand, it is necessary to add to the system approximately 42,000 MW capacity by the end of 2010 and 86,000 MW by the end of 2020. This translates into an annual addition of nearly 4000

MW capacity to the existing system until the year 2010. The annual cost of this investment will increase to approximately US$ 4–5 billion with additional investments to be made for the transmission and distribution system.

3. Turkey's energy sustainability and the role of geothermal energy

Energy has deep and broad relationships with each of the three pillars of sustainable development such as the economy, the environment and social welfare. It remains a strategy commodity: social and economic development can be attained only so long as a secure, reliable and affordable supply of energy is ensured. Energy services help to fulfil basic needs such as food and shelter. They contribute to social development by improving education and public health and, overall, help alleviate poverty. Access to modern energy services can be environmentally beneficial, for example, by reducing deforestation and decreasing pollution through more efficient energy use. On the other hand, these different dimensions are intrinsically linked. Sustainable development is dependent upon balancing the interplay of policies and their effective implementation to achieve economic, environmental and social needs. Economic growth requires a secure and reliable energy supply, but is sustainable only if it does not threaten the environment or social welfare. Environmental quality is more readily protected if basic economic needs are also met, and social development needs both economic growth and a healthy environment. Sometimes the policies are mutually reinforcing and sometimes they are in conflict, and trade-offs will often need to be made. Lower fuel prices widen access to energy, but also encourage inefficient utilization of energy resources and accelerated resource depletion. Conversely, if energy prices are raised too quickly in an effort to combat environmental concerns, energy may become too costly and thus placed beyond the reach of those who need it most [8,9].

Turkish energy policy endeavors to assure energy supply; reliably, sufficiently, on time, economically, with consideration for environmental impacts, and in a way that supports and orients targeted growth and social developments. The government focused its efforts on improvement in domestic production by utilizing public, private and foreign utilities and increasing efficiency by rehabilitation and acceleration of existing construction programmes to initiate new investments. On the other hand, energy use in Turkey has increased steadily with economic and population growth. The present status and projections of the installed capacity of electricity in Turkey are given in Table 2. The table also shows the situation of geothermal power production as compared to the other sources of electricity as of 2000 and projection for 2005.

Turkey is poor in fossil fuel reserves as shown in Table 3. Fossil fuel reserves, production rates in 2001, and estimated sustainability years are given in Table 3. Excluding lignite, the coal, oil, and natural gas reserves in the country are quite scant and are far from meeting the domestic demand. On the other hand, Turkey rich in renewables such as geothermal, solar, wind, biomass and hydropower as explained on the previous papers [5,6]. The studies on renewable energy sources in

Table 2
Installed capacity, production capacity and production values in electricity according to fuel types

	2000			2005		
	Installed capacity (MW)	Average production (GWh)	Current production (GWh)	Installed capacity (MW)	Average production (GWh)	Current production (GWh)
Hard coal	335	2178	3100	1545	10,678	10,500
Lignite	6669	43,649	36,600	8514	55,629	43,600
Fuel-oil	1287	7575	7260	1287	7575	6000
Diesel and LPG	335	1904	1600	1182	8316	6500
Natural gas	6411	44,155	44,140	13,929	90,938	78,400
Others	14	76	160	54	316	250
Multi fuel[a]	1153	6920	–	800	5200	–
Thermal	16,204	106,456	92,860	27,311	178,652	145,250
Hydraulic	11,115	39,652	31,100	14,780	52,831	46,600
Geothermal	15	90	80	40	277	235
Wind	48	157	145	643	1926	1800
Biogas-waste	10	30	15	10	30	15
Total	27,391	146,385	124,200	42,783	233,716	193,900

Source: Ref. [7].
[a] Current production has been distributed according to fuel ratios.

Turkey were started in 1960s but could not exhibit a significant progress by the present time except hydropower. Geothermal resources of the country are wide spread but the favourable reserve for heating and generating electricity is limited and even this limited reserve has not yet been used. Geothermal electricity generation has a minor role in Turkey's electricity capacity as low as 0.09% (see Table 2) but the projections, foresee an improvement to 0.40% by the year of 2030. Opposing the electricity generation, geothermal heat capacity is improving faster.

Table 3
Fossil fuel reserves, production rates in 2001, and sustainability years

Fuel	Reserves (Mtoe)		Production in 2001 (kton/year)	Sustainability years
	Recoverable	Total possible		
Coal	170	1126	1255	53[a]
Lignite	7120	8130	12,772	103[b]
Petroleum	130	130	2679	30[c]
Natural gas (10^6 m^3)	20	20	284	23[d]
Asphalts	40	75	20	120
Bitumens	830	1490	–	–
Uranium (kton)	9.2	9.2	–	–
Thorium (kton)	–	380	–	–

[a] Future production as that of 2001, based on the last 15 years.
[b] With 0.006% increase in future production, based on the last 10 years.
[c] With 0.005% increase in future production, based on the last 15 years.
[d] With 0.09% increase in future production, based on the last 10 years.

4. Geothermal energy activities in Turkey

Beginning of the geothermal energy exploration in Turkey goes back to 1962. MTA, in cooperation with the United Nations Development Programme, conducted an inventory study on the distribution of hot-water springs and potential geothermal fields over the territory. In this survey, geological, geophysical, geomorphological, and geochemical methods were used and a number of wells drilled at prospective sites [9,10].

In addition to the known hot-water sources utilized as balneological centers, some new areas with considerable geothermal energy potential were discovered. It was then proved that the Anatolian territory consists of a young tectonic belt and has numerous grabens, volcanic activities, hydrothermal alterations, fumaroles, and more than 600 hot water resources with temperatures between 20 and 100 °C. Among the high-enthalpy zones, the most important geothermal fields are as follows [10,11]:

(a) *Denizli-Kızıldere field:* Turkey's first commercial geothermal power plant, installed in the Denizli-Kızıldere field was discovered by the MTA in 1968. Kızıldere geothermal field is located near the city of Denizli (31 km away from the city's center). Denizli is located in the southwest inland of Anatolia (Fig. 3), and is a center of tourism with its thermal spas, and historical and cultural diversity. The city has a population close to 500,000, and has a variety of commercial, industrial, and touristic installations. Kızıldere geothermal power plant was installed in 1984 with an installed capacity of 20.4 MWe. Besides electricity production, the resources of this field are also used for dry ice production (40,000 ton/year), greenhouse heating (close to 6000 m^2), bleaching process in a textile industry, and space heating of offices and residences.

(b) *Aydın-Germencik field:* This area is placed on 100 km west of Kızıldere in western Anatolia. After geological, geophysical and geochemical studies, 10 explo-

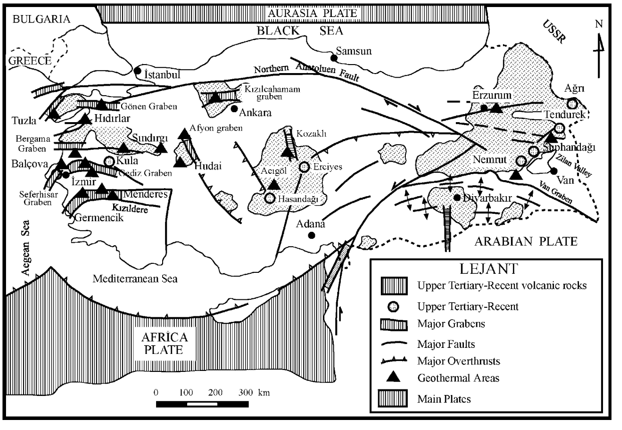

Fig. 3. General tectonic, volcanic features and important geothermal fields in Turkey [11].

ration wells with depths between 285–2398 m have been drilled. The temperatures of the first and second reservoirs are found to be 203–217 °C and 216–232 °C. The average flow rate is 300 tone/h and steam ratio changes from 13 to 20%. The collected data indicate that the field has important geothermal potential. Disposed hot water can be used in electricity generation, district heating, industry and in touristic and balneological centers. A binary cycle power plant with an installed capacity of 25 MWe will be constructed at Aydın/Germencik in 2004.

(c) *Izmir-Seferihisar field:* Between 1986–1997 period, 15 wells were drilled and the reservoir temperature was measured as 153 °C. The 9.7 MW_t heat is discharged from five wells by downhole heat exchanger system. It is estimated that 3600 m^2 greenhouse can be heated with this energy.

(d) *Aydın-Salavatlı field:* This field is placed in nearly in the middle part of the Kızıldere and Germencik fields. Ten wells were drilled in the field between 1987–1998. The total flow rate was found to be 600 t/h and the reservoir temperature was between 162–171 °C.

(e) *Other fields:* The other fields have reservoir temperatures lower than 200 °C can be as Canakkale-Tuzla (174 °C), Kütahya-Simav (162 °C), İzmir-Balçova (126 °C), Afyon-Ömer (106 °C) and Ankara-Kızılcahamam (106 °C).

5. Geothermal energy use in Turkey

As the district heating system installation started with geothermal district heating system (GDHS) investments in Turkey, the GDHS are operated very economical, which is the result of optimization of the geothermal resource characteristics with the consumer's characteristics, suitable system design and technology. On the other hand, Turkey is a developing country and there is a continuous migration from rural areas to cities with 2% population increase annually. As a result of this, apartment buildings in cities are continuously increasing vertically and horizontally. The results of the migration are some of the important subjects should be considered before the establishment of geothermal energy systems. Another case is, while some of the buildings have a radiator-heating systems, some of them have not in the cities of the country. So, the conversion project should take these types of systems into consideration [12].

People in Turkey usually live in apartment houses in cities and in these buildings, the heating system is formed by means of a boiler-radiator system for each building or each flat with its own heating system. In the country, the heating systems, other than geothermal heating systems, are designed with a 90/70 °C temperature interval. Local or imported coal, fuel oil or natural gas is usually used in these heating systems. The prices of these fuels are determined in international market conditions and passed on to the consumers. Due to the high imported fuel costs, in some cities has rich geothermal potential, such as Izmir, Denizli, Kırşehir, district heating systems are now being converted to geothermal energy use in Turkey. The operational capacities of the geothermal district heating systems (GDHS)

Table 4
Operational capacities of the existing city-based GDHS and their integrated geothermal applications in Turkey

Town	Geothermal heating capacity (in residential equivalent)	Integrated geothermal application	Year of start-up	Geothermal water temperature (°C)	Geothermal heating fee paid by the customer (US$) 2002/2003 winter season
Gönen	3400	B, I	1987	80	27
Simav	3200	B, G	1991	120	26
Kirsehir	1800	B	1994	57	21
Kızılcahamam	2500	B, G	1995	80	21
İzmir-Balcova	11,500	B	1996	137	19
Afyon	4500	G	1996	95	25
Kozaklı	1000	G	1996	90	28
İzmir-Narlıdere	1500	–	1998	98	19
Diyadin	400	B	1999	70	–
Sandıklı	2000/5000	B	2000	70	14
Salihli	2000/20,000	B	2002	94	15

B, balneology; I, industrial use; G, greenhouse.
Source: Ref. [14]

and their integrated geothermal applications in Turkey are reported in Table 4. The important points related to this conversion are given as [13,14]:

1. Since the price of geothermal heat is held constant for the entire year, geothermal heating projects are, thus, supported by the consumers.
2. The existing heating systems are connected to GDHS directly.
3. The radiator area designed according to 90/70 °C temperature interval, has not caused any problem at temperature intervals like 80/40, 80/45 and 70/50 °C. The result is that the radiator areas have been designed larger than necessary.

Turkey is one of the countries with significant potential in geothermal energy. Data accumulated since 1962 show that there may exist about 4500 MW of geothermal energy usable for electrical power generation in high enthalpy zones. Exploration of the Kizildere (Denizli) field began in 1968. In 1975, a 0.5 MW_e pilot plant was built and, in February 1984, a 20.4 MW_e (gross)/15 MW_e (net) single flash power plant was installed. Table 5 shows geothermal electric production by the years in Kızıldere power plant. There are nine production wells. Reservoir temperature at about 2000 m depth is 242 °C and the resource carries 1.5% non-condensable gases, primarily CO_2. Extensive $CaCO_3$ scale deposition required frequent cleaning until use of the scale inhibitor Dequest 2066 was begun. Though detailed information regarding the outcome of the scale inhibition has not been reported, scaling now is claimed to have diminished; the average plant output is, however, only 12–15 MW_e. Reinjection has been required by the high concentration (25–30 mg/l)

Table 5
Electric production by the Kızıldere power plant

Years	Production (kWh)	Average production (MW)
1984	22,169,400	6065
1985	5,950,300	4426
1986	43,539,300	5948
1987	57,874,900	6870
1988	68,396,300	10,741
1989	62,645,400	8248
1990	80,112,200	9873
1991	81,307,400	10,226
1992	69,598,800	9807
1993	77,596,800	9811
1994	79,110,500	11,156
1995	85,993,100	10,590
1996	83,688,800	10,312
1997	82,744,800	10,182
1998	85,056,400	9855
1999	79,000,000	9486

Source: Ref. [9].

of boron in the resource. Studies to identify the optimum reinjection sites, depths and techniques are under way. The economic returns on this technically challenging installation have been improved by construction of a 40,000 tons per year liquid carbon dioxide and dry ice plant that is integrated with the power plant [15].

Heating capacity in the country runs at 665 MW_t equivalent to 61,000 residences. These numbers can be heightened some seven-fold to 2520 MW_t equal to 350,000 households through a proven and exhaustible potential in 2000 (Table 6).

Table 6
Status of geothermal space heating in Turkey (MW_t)

	Space heating capacity variations by the years					
	1996	1997	1998	1999	2000	2010
İzmir-Balçova	50	70	100	120	180	380
Balıkesir-Gönen	35	35	40	50	55	300
Denizli-Kızıldere	40	80	120	160	200	600
İzmir-Seferihisar	80	120	150	250	260	450
İzmir-Dikili	40	50	70	90	100	300
Çanakkale-Tuzla	100	200	300	380	500	900
Kütahta-Simav	80	100	120	160	200	340
Afyon	70	90	110	140	180	500
Tokat-Reşadiye	10	12	15	20	25	100
Nevşehir-Kozaklı	25	35	50	70	90	300
Manisa-Salihli	47	80	100	110	110	400
Aydın-Salavatlı	100	200	300	380	500	1600
Diğerleri	150	175	215	260	310	600
Total	802	1192	1775	2065	2520	6500

Source: Ref. [9].

Turkey must target 1.3 million house holds equivalent 7700 MWt. Geothermal central heating, which is less costly than natural gas could be feasible for many regions in the country. In addition 31,000 MW of geothermal energy potential is estimated for direct use in thermal applications. The total geothermal energy potential of Turkey is about 2468 MW in 2001, but the share of geothermal energy production, both for electrical and thermal uses is only 1200 MW. There are 26 geothermal district heating systems exist now in Turkey. Main city geothermal district heating systems are in Gönen, Simav and Kırşehir cities. The Turkish geothermists claim to have virtually overcome the consequences of scaling and corrosion in both high and low temperature wells, so it know that scientific research continues. Plans are to be generating 125 MW_e from Germencik, Kızıldere, Çanakkale and several of the other fields by the year 2000, 150 MW_e by 2005 and 258 MW_e by 2010. Table 7 gives a detailed summary of the present status of the various types of direct use of geothermal energy in Turkey [13].

Greenhouse heating by geothermal energy is gaining more and more importance in Turkey. During last years, strategical importance of food production and agricultural policies have stimulated a wide research work and investigations on new methods for the exploration of available geothermal energy for greenhouse heating in the country. Locations and areas of geothermal greenhouses are shown in Table 8. In Turkey, the first greenhouse heating system of 0.45 ha by geothermal energy was applied in Denizli-Kizildere geothermal field in 1985 and has grown to 1.075 ha today. Recently, the total area of greenhouses heated by geothermal energy has shown a rapid growth totalling an area of about 31 ha and heating capacity of 69.61 MW_t for an average heat load of 2.25 MW_t ha^{-1} [13–16].

Geothermal district heating systems are the main geothermal utilization in Turkey, which have an important meaning to the Turkish citizens who make use of this system; since, a clean environment and comfort has been provided to residences in an economic situation. If a suitable technology selection and professional application, the investment amount per residence of the GDHS is about US$ 1500–2500 excluding radiator installation in Turkey. The geothermal district heating investments are paying back in 5–8 years in the conditions of Turkey. Moreover, they have a relatively low initial and operation costs and low selling price of heat in comparison to conventional fuels such as coal, lignite and fuel-oil. For example, the heating price of geothermal energy is varying from one-fourth to one-seven of heating with natural gas in Turkey. By applying these technical developments to the GDHS, the heating fees in heating season of 2001 are varies from US$ 15 to 30 in Turkey. On the other hand, the construction costs for a heating system is about US$ 350 per kWh as an installed capacity in the country's conditions. About 30–50% of the GDHS investments has been paid by the consumers as a connection subscription fee, like a capital investment. As a result, the economy of the geothermal heating system in Turkey is in a better position.

Table 7
Direct use of geothermal energy in Turkey

System	Capacity (MW_t)	Application	Temperature (°C)
Adapazarı-Kuzuluk	11.2	B, H	98
Adapazarı-Sapanca	0.0216	HP	
Afyon	24.9	R	95
Afyon-Bolvadin	1.05	H	
Afyon-Gazlıgöl Thermal Resort	0.64	B, H	68
Afyon-Omer Thermal Facilities	3.888	B, H, G	98
Afyon-Orucoğlu Thermal Resort	2.7	B, H	48
Afyon-Sandıklı	37	R	70
Ankara-Haymana	0.09	B, M	34–45
Ankara-Kızılcahamam	21.315	R, B, H, G	80
Aydın-Germencik	0.1125	G	35
Balıkesir-Edremit	9.815	G	53–60
Balıkesir-Gönen	37.45	R, H, B, G, I	80
Balıkesir-Havran-Dernek	1.35	G	
Balıkesir-Sindirgi	1.6	G	57–150
Çanakkale-Ezine-Kestanbol	3.82	R, G	62.5–73
Denizli-Golemezli	0.225	B, G	65
Denizli-Kızıldere	2.419	R, G, I	90–147
Istanbul	0.4053	HP	
Izmir-Balcova	87.03	R, G, B, H, S, Ho	40–125
Izmir-Bergama	0.45	B, G	35–100
Izmir-Dikili	2.25	G	90
Izmir-Seferihisar	1.35	B, G	65–140
Kırşehir	19	R	57
Kütahya-Gediz	0.61	B, H, G	78–104
Kütahya-Simav	60	R, G, B, H	137
Kütahya-Yoncalı	0.93	B, H	90
Manisa-Alaşehir	0.26	B, H	30–73
Manisa-Salihli	0.26	B, H	30–168
Mersin	0.099	HP	
Nevşehir-Kozaklı	12	R, G	42–95
Rize-Ayder	0.24	B, H	55
Samsun-Havza	0.07	B, H	54
Sıvas-Sıcak Cermik	0.17	B, H	36–70
Tokat-Niksar	0.1125	G	27–54
Urfa-Kircaali	9.28	G	50
Yalova	0.135	G	48–66.2
Yozgat-Saraykent	0.45	G	46
Sub total	354.642		
Other spas	285	B	
Grand total	639.642		

B, balneology; M, mosque; G, greenhouse; R, space/district heating; H, hotel; S, swimming pool; Ho, hospital; I, industrial application; HP, heat pump.
Source: Ref. [13].

Table 8
Locations and areas of geothermal greenhouses in Turkey

Location	Area (ha)
Afyon-Omer	0.55
Ankara-Kizilcahamam	0.14
Aydın-Germencik	0.05
Balıkesir-Edremit	4.36
Balıkesir-Gönen	0.2
Balıkesir-Havran-Dernek	0.6
Balıkesir-Sindirgi	0.5
Canakkale-Ezine-Kestanbul	0.2
Denizli-Golemezli	0.1
Denizli-Kızıldere	1.0
Denizli-Tekkehamam	0.8
Izmir-Balcova	0.9
Izmir-Bergama	0.2
Izmir-Dikili	1.0
Izmir-Seferihisar	0.6
Kütahya-Gediz	0.85
Kütahya-Simav	12.0
Nevşehir-Kozaklı	0.4
Tokat-Niksar	0.05
Urfa-Kırcaali	6.1
Yalova	0.06
Yozzgat-Saraykent	0.2
Total	30.94

Source: Ref. [9].

5.1. Geothermal heat pumps

Geothermal heat pumps are heat pumps that draw energy from or deposit energy to the ground or groundwater. In the winter, a geothermal heat pump (GHP) transfers thermal energy from the ground or groundwater to provide space heating. In the summer, the energy transfer process is reversed; the ground or groundwater absorbs thermal energy from the conditioned space and cools the air. A GHP benefits from the nearly constant year round ground and groundwater. These temperatures are higher on average than winter air temperatures and lower on average than summer temperatures. The heat pump does not have to work as hard to extract thermal energy from or transfer energy to the ground or groundwater at a moderate temperature as from the cold air in winter or hot air in summer. The energy efficiency of a GHP is thus higher than that of a conventional air-source heat pump (ASHP). Many GHPs are also more efficient than fossil fuel furnaces in the heating mode.

Each system may also have a desuperheater to supplement the building's water heater, or a full-demand water heater to meet all of the building's hot water needs. The desuperheater transfers excess thermal energy from the GHP's compressor to a hot water tank. In summer, hot water is provided free; in the winter, water heating

costs can be reduced by up to 50%. Although residential GHPs are generally more expensive to install than ASHPs, they operate more efficiently than ASHPs. GHPs can also be installed without a backup heat source over a very wide range of climates. For commercial buildings, GHPs are very competitive with boilers, chillers, and cooling towers. On the other hands, the primary difference between an ASHP and a GHP is the investment in a ground loop for energy collection and rejection that is required for the GHP system. Whether a GHP is cost effective relative to a conventional ASHP depends upon generating annual energy cost savings that are high enough to pay for the ground loop in a relatively short time [17].

The concept of GHP or ground source heat pump (GSHP) is not new in Turkey, but the usage of GHPs in residential sector is new, although they have been in use for years in developed countries. In other words, GHPs have been placed in the Turkish market for about 4 years. There are no Turkish GHPs' manufacturers yet. The majority of the installations are in the Marmara region of Turkey, especially in Istanbul and high-income earners also prefer these systems. It is estimated that over 30 units are presently installed in Turkey, representing total capacity of 760 kW. Considering the ongoing installations, it appears that the growth rate will increase in the next years [13].

In Turkish universities, limited studies have been performed on GSHPs. Two experimental MSc and PhD theses [18,19] in the mechanical engineering department have been reported on GSHPs, while theoretical studies [20–22] were relatively more in number. In this regard, Babur [20] designed a single pipe horizontal coupled heat pump system operating with the refrigerant R-12 on the ground to air basis and constructed using available equipment in the Mechanical Engineering Department, Middle East Technical University (METU). He performed 44 runs of experiments during the 1985–1986 heating season under varying climatic conditions to determine the coefficient of performance (COP) and changes in soil temperatures. Approximately 10 m of ground coil was installed at 1.5 m depth with a spacing of 0.6 m. The COP value for heating was found to vary from 1.1 to 1.3. On the other hand, Kara [19] investigated both experimentally and theoretically the utilization of low temperature resources for space heating of a health resort centre in Erzurum by using a GSHP system coupled to geothermal wells. The wells are used just for health care, and the temperature of the disposed water from the baths is around 30 to 35 $^{\circ}$C. Considering these temperature limits, Kara designed a water-to-water ground heat pump system running with R-22 to evaluate the wells mentione above for space heating and developed a computer simulation for the system. The system produced water at 45 $^{\circ}$C for a floor heating system by using the geothermal resource at 35 $^{\circ}$C. The COP for heating was 2.8.

Hepbasli et al. [23] have been performed an experimental study to investigate the performance characteristics of a GSHP system with a 50 m vertical U-bend ground heat exchanger. This system was installed in a room has 65 m^2 floor area in the Solar Energy Institute, Ege University, Izmir, Turkey. The heating and cooling loads of the room were 3.8 and 4.2 kW at design conditions, respectively. Based upon the measurements made in the heating mode, the heat extraction rate from the soil, with an average thermal diffusivity of 0.00375 m^2/h, was found to be, on

average, 11 W/m of bore depth, while the required borehole length in meter per kW of heating capacity was obtained as 14.7. The entering water temperature to the unit ranged from 5.5 to 13.2 °C, with an average value of 8 °C. The heating COP of the heat pump and the whole system was extremely low when compared to other heat pumps operating under conditions at or near design values.

In Turkey, industrial usage of geothermal energy is not common. The most well-known application is liquid CO_2 and dry-ice production process operating adjacent to the Denizli-Kızıldere geothermal power plant since 1986. The process produces 40,000 ton/year and meets 95% of the country's domestic consumption. Another industrial usage in the region is in textile industry using chemical properties of geothermal fluid as a whitening material. In Balıkesir-Gönen, the wastewater of the district heating system has been used for process hot water supply of 54 tanneries [24–26].

6. Conclusions

Geothermal energy has been produced commercially for 70 years, and on the scale of hundreds of MW for four decades, both for electricity generation and direct use. The utilization has increased rapidly during the last three decades. In 2000, there are records of geothermal utilization in 58 countries in the world. The electricity generated is about 49 TWh/year, and the direct use amounts to about 53 TWh/year. On the other hand, geothermal energy, with its proven technology and abundant resources, can make a significant contribution towards reducing the emission of greenhouse gases worldwide. However, environmental and social dimensions of geothermal development must be carefully and properly managed. It is necessary for governments to implement a legal and institutional framework and fiscal instruments allowing geothermal resources to compete with conventional energy systems.

Turkey is one of the countries with significant potential in geothermal energy. The data accumulated since 1962 show that the estimated geothermal power and direct use potential are about 4500 MW_e and 31,500 MW_t, respectively. The direct use capacity in thermal applications is in total 660 MW_t representing only 3% of its total potential. Since 1990, space heating and greenhouse developments have exhibited a significant progress. The total area of greenhouses heated by geothermal energy reached up to about 35 ha with a heating capacity of about 70 MW_t. A geothermal power plant with a installed capacity of 20.4 MW_e has been operated in the Denizli-Kizildere field since 1984. Geothermal energy offers technically and economically feasible possibilities for development of different agricultural production sectors in Turkey. On the other hand, ground source heat pumps (GSHPs) have been used in domestic buildings for heating and cooling since 1998. New financing mechanisms are needed to promote investment in energy efficiency and renewable energy which will support the development of GSHPs. Present applications have shown that geothermal energy in Turkey and in other countries is clean and cheaper than the other fossil and renewable energy sources and therefore is a

Table 9
Capacities in geothermal utilization in Turkey (August 2003)

Geothermal utilization	Capacity
District heating	665 MW_t
Balneological utilization	327 MW_t
Total direct use	992 MW_t
Power production	20.4 MW_e
Carbon dioxide production	120,000 t/year

Source: Refs. [14,25].

promising alternative. As the geothermal energy projects are supporting by the governments and private companies, then the progress will continue (Tables 9 and 10). The main conclusions that can be drawn from the present study on the utilization of geothermal and other renewable energy sources for sustainable future in Turkey are listed below [12–26]:

- Geothermal energy is clean, inexpensive, domestic, and renewable energy source for Turkey. It can be utilized in various forms such as space heating and domestic hot water supply, CO_2 and dry ice production processes, geothermal heat pumps, greenhouse heating, swimming and balneology (therapeutic baths), industrial process heat, and electricity generation.
- Geothermal energy is very important, since energy shortages have increased rapidly and Turkey is an energy importing country.
- Although geothermal energy has a wide utilization area according to different temperatures, its utilization area in the country is mostly space heating.
- Geothermal energy offers technically and economically feasible possibilities for development of different agricultural production sectors in Turkey.
- Although Turkey has no specific laws for development of geothermal energy yet and the lack of governmental support, direct use applications have been growing

Table 10
Present and future geothermal heat and electricity generation projections in Turkey

Years	Total capacity (MW_e)	Electricity generation (GWh)	Thermal generation (MW_t)	TEP (×1000) (thermal)
2002	20	90	965	430,721
2003	45	202.5	1187	511,462
2004	60	202.5	2122	914,341
2005	100	360	2926	1,260,774
2010	300	1250	3765	1,622,288
2015	400	2150	4670	2,145,410
2020	600	3500	6365	2,742,610
2025	1250	4625	8182	3,225,660
2030	1500	5625	10,150	3,890,545

Source: Ref. [9].

rapidly and proven by public sector due to the geothermal heating is about 65 % cheaper than natural gas heating.

- The number of the existing 170 wells located in some geothermal fields is not enough for Turkey's geothermal potential. At least 100 new wells per year should be drilled. Turkey is ready for international cooperation and finance for geothermal exploration and field development projects.
- GHP systems are promising new energy technology that has shown an increase in usage recent years in Turkey. In order to penetrate GHPs successfully to the Turkish market, some keys should be taken into account such as increase of technology awareness, first cost reduction and provision of financial assistance to end users.
- By heating 61,000 residences equivalence by geothermal energy in Turkey, approximately 600,000 tons of CO_2 emission has not been discharged to the atmosphere. This is equivalent to avoiding 340,000 cars from the traffic (as of peak emission amount in January) and 700 0000 ton per year oil saving.
- As the price of electricity in Turkey is high, heat pump utilization is not widespread. But, the utilization of the heat pumps should be supported by the governments due to their high energy efficiency depends on electrical-resistance heating and environmental friendly properties.

References

[1] UNDP. World Energy Assessment report, New York: United Nations; 2000.

[2] World Energy Council (WEC). WEC survey of energy resources 2001. WEC, 2002.

[3] Barbier E. Geothermal energy technology and current status: an overview. Renew Sustain Energy Rev 2002;6:3–65.

[4] Imbach T. Deep groundwater circulation in the techtonically active area of Bursa, Northwest Anatolia, Turkey. Geothermics 1997;26:251–78.

[5] Kaygusuz K. Environmental impacts of energy utilization and renewable energy policies in Turkey. Energy Policy 2002;30:689–98.

[6] Kaygusuz K, Kaygusuz A. Energy and sustainable development in Turkey. Part I: energy utilization and sustainability. Energy Sources 2002;24:483–93.

[7] Ministry of Energy and Natural Resources (MENR). Energy report of Turkey. Ankara, Turkey, 2002. Available from http://www.menr.gov.tr

[8] OECD/IEA. Energy policies of IEA countries: Turkey 2001 Review, OECD, Paris, 2001.

[9] State Planning Organization (SPO). Eighth Five-Year Development Plan. Geothermal Energy Special Impression Commission Report (in Turkish). DPT, 2001, Ankara, Turkey.

[10] Erişen B, Akkuş I, Uygur N, Koçak A. Geothermal Inventory of Turkey (in Turkish). Mineral Exploration and Research Directorate, MTA, 1996, Ankara, Turkey.

[11] Şimşek Ş. Importance of geothermal energy in Turkey. Int. Mediterranean Congress on Solar and Other New-Renewable Energy Resources, Antalya, Turkey. 1988.

[12] Mertoğlu O. Geothermal district heating experience in Turkey. GHC Bulletin 2001;21:14–8.

[13] Gunerhan GG, Kocar G, Hepbasli A. Geothermal energy utilization in Turkey. Int.J Energy Res 2001;25:769–84.

[14] Mertoğlu O, Bakır N, Kaya T. Geothermal applications in Turkey. Geothermics 2003;32:419–28.

[15] Mertoğlu M, Özbek T, Şimşek Ş, Kara H, Kanyılmaz N. Present situation of geothermal energy in the world and in Turkey. Turk J Geotherm 2000;2:13–7.

[16] Kocar G, Eltez M. Effective use of geothermal energy for greenhouses in Balcova-Izmir region. Energy and the environment. New York: Begell House; 1999, p. 217–20.
[17] 1995 ASHRAE HVAC Applications Handbook (SI). ASHRAE, Atlanta, 1995.
[18] Babur N. Design and construction of an earth source heat pump. MSc thesis, Mechanical Engineering Department, Middle East Technical University, Ankara, Turkey: 1986
[19] Kara Y. Utilization of low temperature geothermal resources for space heating by using geothermal heat pumps. PhD thesis, Atatürk University, Erzurum, Turkey: 1999. p. 151.
[20] Kılkış B. Methods of utilization of soil heat by using heat pumps in residential areas built outside urban zones. J Thermal Sci Tech 1981;4:21–5.
[21] Hepbaslı A. Heat pump systems and a storey-house heating. MSc thesis, Istanbul Technical University, Istanbul, Turkey, 1985, p. 134.
[22] Ataman H. Design of ground-source heat pump systems. MSc thesis, Istanbul Technical University, Department of Mechanical Engineering, Istanbul, Turkey: 1991. p.151
[23] Hepbasli A, Akdemir O, Hancıoğlu E. Experimental study of a closed loop vertical ground source heat pump system. Energy Convers Mgmt 2003;44:527–48.
[24] Kaygusuz K, Kaygusuz A. Geothermal energy: power for a sustainable future. Energy Sources 2002;24:937–47.
[25] Geothermal energy in Turkey, available from http://www.jeotermaldernegi.org.tr
[26] Geothermal as Green energy, The Bulletin of Turkish Geothermal Association, August 2000 (Vol.2) and September 2001 (Vol. 3).